

CLAIMS

I claim:

1. A fail-safe apparatus for controlling fluid flow through a series arrangement of first and second valves, wherein the fail-safe apparatus is operable at any of a plurality of switching
5 cycles, wherein each of the plurality of switching cycles defines successive on and off states each having a given duration, wherein the duration of the successive on and off states defines one of a plurality of duty cycles, the fail-safe apparatus comprising:

a first solenoid coil for controlling operation of the first valve between an unactuated state and an actuated state;

10 a second solenoid coil for controlling operation of the second valve between an unactuated state and an actuated state;

a switch operable to couple during the on state of any of the plurality of duty cycles an input voltage across the first solenoid coil to cause a first current to flow therein; and

15 an energy-transfer device coupling the first solenoid coil with the second solenoid coil, the energy-transfer device operable to store energy therein, wherein:

(i) during the on state of at least one of the plurality of duty cycles, a potential established in the energy-transfer device in combination with the input voltage causes a second current to flow in the second solenoid coil,

20 (ii) during the off state of any of the plurality of duty cycles, the potential established in the energy-transfer device affects a decay rate of any first and second current flowing through their respective first and second solenoid coils, and

(iii) when the first and second currents exceed respective first and second thresholds, the first and second solenoid coils cause their respective valves to operate in
25 the actuated state.

2. The fail-safe apparatus recited in claim 1, wherein when the first valve is operating in the actuated state and an average of the first current is maintained above a third threshold over any of the plurality of switching cycles, the first valve is maintained in the actuated state.

5 3. The fail-safe apparatus recited in claim 2, wherein when the second valve is operating in the actuated state and an average of the second current is maintained above a fourth threshold over any of the plurality of switching cycles, the second valve is maintained in the actuated state.

10 4. The fail-safe apparatus recited in claim 1, wherein when the second valve is operating in the actuated state and an average of the second current is maintained above a fourth threshold over any of the plurality of switching cycles, the second valve is maintained in the actuated state.

15 5. The fail-safe apparatus recited in claim 1, wherein the plurality of duty cycles defines a high duty cycle having an on-state duration of approximately 70 to 100 percent of a given switching cycle, wherein during the on state, the switch couples the input voltage across the first solenoid coil so as to cause the first current to exceed the first threshold, thereby causing the first valve to operate in the actuated state; and wherein during the off state, the potential established in the energy transfer helps to maintain the first current so as to maintain the first valve in the actuated state.

20 6. The fail-safe apparatus recited in claim 5, wherein after the switch decouples the input voltage, the first current freewheels causing at least a portion of the energy stored in the energy-transfer device to deplete, and wherein after the switch couples the input voltage across the first solenoid coil, the input voltage replenishes the depleted portion of the energy stored in the
25 energy-transfer device.

7. The fail-safe apparatus recited in claim 5, wherein the potential established in the energy-transfer device has a positive polarity from between the first solenoid coil to the second solenoid coil.

5 8. The fail-safe apparatus recited in claim 5, wherein during the on and off states, the potential established in the energy-transfer device limits the second current flow so as to cause the second current to be below the second threshold, thereby causing the second valve to operate in the unactuated state.

10 9. The fail-safe apparatus recited in claim 1, wherein the plurality of duty cycles defines a low duty cycle having an on state duration of approximately 10 to 30 percent of a given switching cycle, wherein during the on state:

 (i) the switch couples the first voltage across the first solenoid coil so as to cause the first current to be below the first threshold, thereby causing the first valve to operate in the unactuated
15 state, and

 (ii) the potential established in the energy-transfer device in combination with the input voltage causes the second current to exceed the second threshold, thereby causing the second valve to operate in the actuated state; and wherein during the off state:

 (i) the potential established in the energy-transfer device affects the decay rate of the first
20 current so as to maintain the first valve in the unactuated state, and

 (ii) the energy-transfer device provides freewheeling path for the second current so as to maintain the second valve in the actuated state.

10. The fail-safe apparatus recited in claim 9, wherein after the switch decouples the
25 input voltage, the first current freewheels raising the potential established in the energy-transfer

device, and wherein after the switch couples the input voltage across the first solenoid coil, the second current reduces the potential established in the energy-transfer device.

11. The fail-safe apparatus recited in claim 9, wherein the potential established in the
5 energy-transfer device has a positive polarity from between the second solenoid coil to the first solenoid coil.

12. The fail-safe apparatus recited in claim 11, wherein the duration of the on state of the
10 switch limits the first current flow so as to cause the first current to be below the second threshold, thereby causing the first valve to operate in the unactuated state.

13. The fail-safe apparatus recited in claim 1, wherein the plurality of duty cycles defines
a mid-range duty cycle having an on state duration of approximately 50 percent of the given
switching cycle, wherein substantially no net potential is established in the energy-transfer
15 device, wherein during the on state:

(i) the switch couples the input voltage across the first solenoid coil to cause the first
current to exceed the first threshold, thereby causing the first valve to operate in the actuated
state, and

(ii) any transient potential established in the energy-transfer device in combination with
20 the input voltage causes the second current to exceed the second threshold, thereby causing the second valve to operate in the actuated state, and wherein during the off state, the energy-transfer device provides freewheeling paths for the first and second currents so as to maintain the first and second valve in the actuated state.

14. The fail-safe apparatus recited in claim 13, wherein after the switch decouples the input voltage, the energy-transfer device affects the decay rate of freewheeling first and second currents so as to maintain them above third and fourth thresholds, respectively.

5 15. The fail-safe apparatus recited in claim 1, wherein the energy-transfer device comprises a capacitor and rectifier network.

16. The fail-safe apparatus recited in claim 15, wherein the capacitor is device operable to store energy therein, wherein established:(i) during the on state of at least one of the plurality
10 of duty cycles, a potential established in the capacitor in combination with the input voltage causes a second current to flow in the second solenoid coil, (ii) during the off state of any of the plurality of duty cycles, the potential established in the capacitor in combination with the rectifier affects the decay rate of any first current flowing through the first solenoid coil and the rectifier provides a freewheeling path for the second current flowing through the second solenoid
15 coil.

17. The fail-safe apparatus recited in claim 15, wherein when the first valve is operating in the actuated state and an average of the first current is maintained above a third threshold over any of the plurality of switching cycles, the first valve is maintained in the actuated state.

20 18. The fail-safe apparatus recited in claim 16, wherein when the second valve is operating in the actuated state and an average of the second current is maintained above a fourth threshold over any of the plurality of switching cycles, the second valve is maintained in the actuated state.

19. The fail-safe apparatus recited in claim 15, wherein when the second valve is operating in the actuated state and an average of the second current is maintained above a fourth threshold over any of the plurality of switching cycles, the second valve is maintained in the actuated state.

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20. The fail-safe apparatus recited in claim 15, wherein the plurality of duty cycles defines a high duty cycle having an on-state duration of approximately 70 to 100 percent of a given switching cycle, wherein during the on state, the switch couples the input voltage across the first solenoid coil so as to cause the first current to exceed the first threshold, thereby causing
10 the first valve to operate in the actuated state; and wherein during the off state, the potential established in the capacitor helps to maintain the first current so as to maintain the first valve in the actuated state.

21. The fail-safe apparatus recited in claim 20, wherein after the switch decouples the
15 input voltage, the first current freewheels causing at least a portion of the energy stored in the capacitor to deplete, and wherein after the switch couples the input voltage across the first solenoid coil, the input voltage replenishes the depleted portion of the energy stored in the capacitor.

20 22. The fail-safe apparatus recited in claim 20, wherein the first solenoid coil is coupled between a first-common node and a low-side reference node, wherein the capacitor is coupled between the first common node and a second common node; wherein the rectifier is coupled between the second common node and the low-side reference node in such a way to allow forward-bias current flow from the low-side reference node to the second common node;
25 wherein the second solenoid coil is coupled between the second common node and the low-side

reference node, and wherein the potential established in the energy-transfer device has a positive polarity from between first common node and a second common node.

23. The fail-safe apparatus recited in claim 20, wherein during the on and off states, the
5 potential established in the capacitor limits the second current flow below the second threshold, thereby causing the second valve to operate in the unactuated state.

24. The fail-safe apparatus recited in claim 15, wherein the plurality of duty cycles
10 defines a low duty cycle having an on state duration of approximately 10 to 30 percent of a given switching cycle, wherein during the on state:

(i) the switch couples the first voltage across the first solenoid coil so as to cause the first current to be below the first threshold, thereby causing the first valve to operate in the unactuated state, and

(ii) the potential established in the capacitor in combination with the input voltage causes
15 the second current to exceed the second threshold, thereby causing the second valve to operate in the actuated state; and wherein during the off state:

(i) the potential established in the capacitor affects the decay rate of the first current so as to maintain the first valve in the unactuated state, and

(ii) the rectifier provides a freewheeling path for the second current so as to maintain the
20 second valve in the actuated state.

25. The fail-safe apparatus recited in claim 24, wherein after the switch decouples the input voltage, the first current freewheels through the rectifier raising the potential established in the capacitor, and wherein after the switch couples the input voltage across the first solenoid coil,
25 the input voltage causes the second current flowing through the capacitor and thus reduces the potential established in the capacitor.

26. The fail-safe apparatus recited in claim 24, wherein the first solenoid coil is coupled between a first-common node and a low-side reference node, wherein the capacitor is coupled between the first common node and a second common node; wherein the rectifier is coupled
5 between the second common node and the low-side reference node in such a way to allow forward-bias current flow from the low-side reference node to the second common node; wherein the second solenoid coil is coupled between the second common node and the low-side reference node, and wherein the potential established in the capacitor has a positive polarity from between the second common node to the first common node.

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27. The fail-safe apparatus recited in claim 24, wherein the duration of the on state of the switch limits the first current flow so as to cause the first current to be below the second threshold, thereby causing the first valve to operate in the unactuated state.

15 28. The fail-safe apparatus recited in claim 15, wherein the plurality of duty cycles defines a mid-range duty cycle having an on state duration of approximately 50 percent of the given switching cycle, wherein substantially no net potential is established in the capacitor, wherein during the on state:

(i) the switch couples the input voltage across the first solenoid coil to cause the first
20 current to exceed the first threshold, thereby causing the first valve to operate in the actuated state, and

(ii) any transient potential established in the capacitor in combination with the input voltage causes the second current to exceed the second threshold, thereby causing the second valve to operate in the actuated state; and wherein during the off state the substantially no net
25 potential established in the capacitor in combination with the rectifier controls the decay of the first and second currents so as to maintain the first and second valve in the actuated state.

29. The fail-safe apparatus recited in claim 28, wherein after the switch decouples the input voltage, the capacitor in combination with the rectifier affects the decay rate of freewheeling first and second currents so as to maintain them above third and fourth thresholds,
5 respectively.

30. The fail-safe apparatus recited in claim 15, further comprising passive-current-limiting circuitry for limiting first current flow through the first solenoid coil when operating at a duty cycle from about 0.7 to 1, and for limiting the second current flow through the second
10 solenoid coil when operating at a duty cycle from about 0.1 to 0.3.

31. The fail-safe apparatus recited in claim 30, wherein the first solenoid coil is coupled between a first-common node and a low-side reference node, wherein the capacitor is coupled between the first common node and a second common node; wherein the rectifier is coupled
15 between the second common node and the low-side reference node in such a way to allow forward-bias current flow from the low-side reference node to the second common node; wherein the second solenoid coil is coupled between the second common node and the low-side reference node, and wherein the passive-current-limiting circuitry comprises:

first and second resistors in a series arrangement coupled between the switch and the first
20 common node; and

a second capacitor coupled in parallel across the first resistor.

32. The fail-safe apparatus recited in claim 31, wherein the combination of the first and second resistors limit currents flow through the first and second solenoid coils when operating at
25 the duty cycle of about 0.7 to 1, and wherein the second resistor limits currents flow through the

first and second solenoid coils when operating at the duty cycle of about 0.1 to 0.3, while the second capacitor bypasses the first resistor.

33. The fail-safe apparatus recited in claim 1, wherein the switch comprises a
5 transistor, and wherein the duty cycle of the switch is controlled by a control signal.

34 The fail-safe apparatus recited in claim 33, wherein the control signal is supplied by a microprocessor.

10 35. The fail-safe apparatus recited in claim 33, wherein the control signal comprises a pulse-width-modulated signal.

36. The fail-safe apparatus recited in claim 33, wherein the control signal comprises a pulse-frequency-modulated signal.

15 37. The fail-safe apparatus recited in claim 33, wherein the transistor comprises a metal-oxide-field-effect transistor (MOSFET) having a gate, source and drain, and further comprising an alternating-current-coupling circuit coupled to the gate and source of the MOSFET.

20 38. The fail-safe apparatus recited in claim 37, further comprising passive-current-limiting circuitry coupled between the MOSFET and the first solenoid coil or between the power supply and the MOSFET.

25 39. The fail-safe apparatus recited in claim 37, wherein the first solenoid coil is coupled between a first-common node and a low-side reference node, wherein the energy-transfer device is coupled between the first solenoid coil and the second solenoid coil; wherein the second

solenoid coil is coupled between a second common node and the low-side reference node, wherein when the MOSFET is a P-channel enhancement type having its drain coupled to the first common node, the alternating-current-coupling circuit comprises:

a rectifier coupled between the gate and source of the MOSFET, wherein the rectifier
5 allows a forward-bias-current flow from the gate to the source;
a first resistor coupled between the gate and source of the MOSFET; and
a capacitor having a first end coupled to the gate of the MOSFET and a second end for
receiving the control signal

10 40. The fail-safe apparatus recited in claim 39, further comprising:
second and third resistors in a series arrangement coupled between the drain of the
MOSFET and the first common node; and
a second capacitor coupled in parallel across the first resistor.

15 41. The fail-safe apparatus recited in claim 37, wherein the first solenoid coil is coupled
between a first-common node and a third-common node, wherein the energy-transfer device is
coupled between the first solenoid coil and the second solenoid coil; wherein the second solenoid
coil is coupled between a second common node and the third-common node, and wherein when
the MOSFET is a N-channel enhancement type having its source coupled to the low-side
20 reference node, the alternating-current-coupling circuit comprises:

a rectifier coupled between the gate and source of the MOSFET, wherein the rectifier
allows a forward bias current flow from the source to the gate;
a first resistor coupled between the gate and source of the MOSFET; and
a capacitor having a first end coupled to the gate of the MOSFET and a second end for
25 receiving the control signal.

42. The fail-safe apparatus recited in claim 41, further comprising:
second and third resistors in a series arrangement coupled between the power supply and
the first common node; and
a second capacitor coupled in parallel across the first resistor.

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43. The fail-safe apparatus recited in claim 1, further including a direct-current to direct-current (DC-DC) converter operable at a plurality of duty ratios, wherein the DC-DC converter has an output to supply the input voltage.

10 44. The fail-safe apparatus recited in claim 43, wherein the DC-DC converter comprises a regulator in a standard buck-style configuration.

45. The fail-safe apparatus recited in claim 43, wherein the DC-DC converter comprises a regulator in a standard boost-style configuration.

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46. The fail-safe apparatus recited in claim 43, wherein the duty ratio of the DC-DC converter is controlled by pulse-width-modulation.

47. The fail-safe apparatus recited in claim 43, wherein the duty ratio of the DC-DC
20 converter is controlled by pulse-frequency-modulation.

48. The fail-safe apparatus recited in claim 1, wherein the energy-transfer device comprises a first capacitor, a second capacitor, a rectifier, a second switch, and a resistor to limit control current to the second switch.

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49. The fail-safe apparatus recited in claim 48, wherein the second capacitor is a device operable to store energy therein, wherein (i) during the on state and off state of at least one of the plurality of duty cycles, the potential established in the second capacitor in combination with the input voltage biases the second switch to cause a second current to flow in the second solenoid coil, and (ii) during the off state of any of the plurality of duty cycles, the potential established in the first capacitors in combination with the rectifier affects the decay rate of any first current flowing through the first solenoid coil.

50. The fail-safe apparatus recited in claim 48, wherein when the first valve is operating in the actuated state and an average of the first current is maintained above a third threshold over any of the plurality of switching cycles, the first valve is maintained in the actuated state.

51. The fail-safe apparatus recited in claim 50, wherein when the second valve is operating in the actuated state and an average of the second current is maintained above a fourth threshold over any of the plurality of switching cycles, the second valve is maintained in the actuated state.

52. The fail-safe apparatus recited in claim 48, wherein when the second valve is operating in the actuated state and an average of the second current is maintained above a fourth threshold over any of the plurality of switching cycles, the second valve is maintained in the actuated state.

53. The fail-safe apparatus recited in claim 48, wherein the plurality of duty cycles defines a high duty cycle having an on-state duration of approximately 70 to 100 percent of a given switching cycle, wherein during the on state the switch couples the input voltage across the first solenoid coil so as to cause the first current to exceed the first threshold, thereby causing the

first valve to operate in the actuated state, and wherein during the off state, the potential established in the first capacitor affects the decay rate of the first current so as to maintain the first valve in the actuated state.

5 54. The fail-safe apparatus recited in claim 53, wherein after the switch decouples the input voltage, the first current freewheels causing at least a portion of the energy stored in the first capacitor to deplete, and wherein after the switch couples the input voltage across the first solenoid coil, the input voltage replenishes the depleted energy of the potential stored in the first capacitor.

10 55. The fail-safe apparatus recited in claim 53, wherein the first solenoid coil is coupled between a first-common node and a low-side reference node, wherein the first capacitor is coupled between the first common node and the low-side reference, wherein the rectifier is coupled between the first common node and a second common node in such a way to allow
15 forward-bias current flow from the second common node to the first common node, wherein the second capacitor is coupled between the second common node and the low-side reference node, wherein the second switch is coupled between the second common node and the first switch, wherein the second solenoid coil is coupled between a second side of the second switch and the low-side reference node, and wherein the potential established in the second capacitor has a
20 negative polarity from between second common node and the low-side reference node.

 56. The fail-safe apparatus recited in claim 53, wherein during the on and off states the potential established in the second capacitor is insufficient to activate the second switch, thereby causing the second valve to operate in the unactuated state.

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57. The fail-safe apparatus recited in claim 48, wherein the plurality of duty cycles defines a low duty cycle having an on state duration of approximately 10 to 30 percent of a given switching cycle, wherein during the on state:

(i) the switch couples the first voltage across the first solenoid coil so as to cause the first current to be below the first threshold, thereby causing the first valve to operate in the unactuated state, and

(ii) the potential established in the second capacitor in combination with the input voltage biases the second switch to cause the second current to exceed the second threshold, thereby causing the second valve to operate in the actuated state; and wherein during the off state:

(i) the potential established in the first capacitor affects the decay rate of the first current so as to maintain the first valve in the unactuated state, and

(ii) a freewheeling first current increases the potential established in the second capacitor, this potential in combination with the input voltage biases the second switch so as to cause the second current to exceed the second threshold, thereby causing the second valve to operate in the actuated state.

58. The fail-safe apparatus recited in claim 57, wherein after the switch decouples the input voltage, the first current freewheels through the second capacitor and rectifier raising the potential established in the second capacitor.

59. The fail-safe apparatus recited in claim 57, wherein the first solenoid coil is coupled between a first-common node and a low-side reference node, wherein the first capacitor is coupled between the first common node and the low-side reference, wherein the rectifier is coupled between the first common node and a second common node in such a way to allow forward-bias current flow from the second common node to the first common node, wherein the second capacitor is coupled between the second common node and the low-side reference node,

wherein the second switch is coupled between the second common node and the first switch, wherein the second solenoid coil is coupled between a second side of the second switch and the low-side reference node, and wherein the potential established in the second capacitor has a negative polarity from between second common node and the low-side reference node.

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60. The fail-safe apparatus recited in claim 57, wherein the duration of the on state of the switch limits the first current flow so as to cause the first current to be below the second threshold, thereby causing the first valve to operate in the unactuated state.

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61. The fail-safe apparatus recited in claim 48, wherein the plurality of duty cycles defines a mid-range duty cycle having an on state duration of approximately 50 percent of the given switching cycle, wherein a negative potential is established in the second capacitor, wherein during the on state:

(i) the switch couples the input voltage across the first solenoid coil to cause the first
15 current to exceed the first threshold, thereby causing the first valve to operate in the actuated state, and

(ii) the potential established in the second capacitor in combination with the input voltage biases the second switch to cause the second current to exceed the second threshold, thereby causing the second valve to operate in the actuated state; and wherein during the off state:

(i) the potential established in the first capacitor affects the decay rate of the first current
20 so as to maintain the first valve in the actuated state, and

(ii) the freewheeling first current increases the potential established in the second capacitor which in combination with the input voltage biases the second switch to cause the second current to exceed the second threshold, thereby causing the second valve to operate in the
25 actuated state.

62. The fail-safe apparatus recited in claim 61, wherein after the switch decouples the input voltage, the first capacitor and the second capacitor in combination with the rectifier affects the decay of freewheeling first current so as to maintain the first current above third threshold, wherein the freewheeling first current increases the potential in second capacitor, this potential in combination with the input voltage biases the second switch to cause the second current above the fourth threshold.

63. In a fail-safe system for controlling fluid flow through a series arrangement of first and second valves, wherein the fail-safe system is operable at any of a plurality of switching cycles, wherein each of the plurality of switching cycles defines successive on and off states each having a given duration, wherein the duration of the successive on and off states defines one of a plurality of duty cycles, a method for operating the fail-safe system comprising:

(a) applying an input voltage across a first solenoid coil during the on state of any of the plurality of duty cycles so as to cause a first current to flow therein;

(b) during the on state of at least one of the plurality of duty cycles, applying a combination of (i) a potential established in an energy-transfer device and (ii) the input voltage as to cause a second current to flow in a second solenoid coil, wherein the energy-transfer device couples the first solenoid coil with the second solenoid coil;

(c) removing the input voltage from across first solenoid coil during the off state of any of the plurality of duty cycles so as allow the first and second currents to decay; and

(d) using the potential established in the energy-transfer device to affect a decay rate of any first and second current flowing through their respective first and second solenoid coils during the off state of any of the plurality of duty cycles, wherein when the first and second currents exceed respective first and second thresholds, the first and second solenoid coils cause their respective valves to operate in actuated states.

64. The method of claim 63, further comprising:

maintaining an average of the first current above a third threshold over any of the plurality of switching cycles to maintain the first valve in the actuated state; and

5 maintaining an average of the second current above a fourth threshold over any of the plurality of switching cycles to maintain the second valve in the actuated state.

65. The method of claim 64, wherein the plurality of duty cycles defines a high duty cycle having an on-state duration of approximately 70 to 100 percent of a given switching cycle, 10 wherein at the high duty cycle step (a) causes the first current to exceed the first threshold, and step (d) helps to maintain the first current over the third threshold.

66. The method of claim 64, wherein the plurality of duty cycles defines a low duty cycle having an on state duration of approximately 10 to 30 percent of a given switching cycle, 15 wherein at the low duty cycle step (a) causes the first current to be below the first threshold, step (b) causes the second current to exceed the second threshold, and step (d) affects the decay rate of the first current so as to maintain the first valve in the unactuated state, and further comprising using the energy-transfer device as a freewheeling path for the second current to maintain the second valve in the actuated state.

20 67. The method of claim 64, wherein the plurality of duty cycles defines a mid-range duty cycle having an on state duration of approximately 50 percent of the given switching cycle, wherein substantially no net potential is established in the energy-transfer device, and wherein at the mid-range duty cycle, step (a) causes the first current to exceed the first threshold, and step 25 (b) causes the second current to exceed the second threshold, and further comprising using the

energy-transfer device as a freewheeling paths for the first and second currents to maintain the first and second valves in the actuated state.

68. The method of claim 67, wherein step (c) affects the decay rate of the freewheeling
5 first and second currents so as to maintain them above third and fourth thresholds, respectively.